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4 **Evaluation of amendments to control phosphorus losses in** 5 **runoff from pig slurry applications to land**

6

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14

15 **Running Head Title:** Amendment to pig slurry

16

17 **Nonstandard abbreviations:** Flue gas desulphurization by-product (FGD); poly-aluminium
18 chloride (PAC); alum-based water treatment residual (Al-WTR);

19

20 **Keywords:** Agitator test; dissolved reactive phosphorus; land application; pig slurry.

21

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23

24

25 **Abstract**

26

27 If spread in excess of crop requirements, incidental phosphorus (P) losses from agriculture
28 can lead to eutrophication of receiving waters. The use of amendments in targeted areas may
29 help reduce the possibility of surface runoff of nutrients. The aim of this study was to identify
30 amendments which may be effective in reducing incidental dissolved reactive phosphorus
31 (DRP) losses in surface runoff from land applied pig slurry. For this purpose, the DRP losses
32 under simulated conditions across the surface of intact grassland soil cores, loaded with
33 unamended and amended slurry at a rate equivalent to 19 kg P ha^{-1} , were determined over a
34 30 h period. The effectiveness of the amendments at reducing DRP in overlying water were
35 (in decreasing order): alum (86%), flue gas desulphurization by-product (FGD) (74 %), poly-
36 aluminium (Al) chloride (PAC) (73%), ferric chloride (71 %), flyash (58%) and lime (54%).
37 Flue gas desulphurization by-product was the most costly of all the treatments ($\text{€}7.64/\text{m}^3$ for
38 74% removal). Ranked in terms of feasibility, which takes into account effectiveness, cost
39 and other potential impediments to use, they were: alum, ferric chloride, PAC, flyash, lime
40 and FGD.

41

42 **1 Introduction**

43

44 The application of slurry in excess of crop requirements can give rise to elevated soil test
45 phosphorus (P) concentrations, which may take years-to-decades to be reduced to
46 agronomically optimum levels [1]. In addition, it can lead to eutrophication of receiving
47 waters [2]. Phosphorus losses occur in runoff from two sources: a) ‘incidental P losses’ take
48 place when a rainfall event occurs shortly after slurry application and before slurry infiltrates
49 the soil, while b) ‘chronic P losses’ is a long-term loss of P from soil as a result of a build-up

50 in soil test P caused by application of inorganic fertilisers and manure [1, 3]. The use of
51 amendments may allow the application of manure to soil in intensive farm systems, such as
52 pig farms, while reducing incidental and chronic P losses. This paper proposes a novel and
53 relatively realistic way to identify such amendments.

54

55 Alum, aluminium chloride (AlCl_3), lime and ferric chloride are commonly used as coagulants
56 in slurry and wastewater separation operations. Smith et al. [4] found in a field-based study
57 that aluminium chloride, added at 0.75% of final manure volume to pig slurry, could reduce
58 DRP by up to 84%. Smith et al. [5] found that alum and AlCl_3 , added in a field-based study to
59 pig slurry at 430 mg Al L^{-1} , reduced DRP in runoff water by 84% and DRP in manure by
60 over 99%. In an incubation study, Dou et al. [6] found that technical-grade alum, added to pig
61 slurry at 0.25 kg kg^{-1} of manure dry matter, and flue gas desulphurisation by-product (FGD),
62 added at 0.15 kg kg^{-1} , each reduced DRP by 80%. Dao [7] amended stockpiled cattle manure
63 with caliche, alum and flyash in an incubation experiment, and reported water extractable P
64 reductions in amended manure compared to the control of 21, 60 and 85%, respectively.

65

66 Batch experiments, wherein an amendment and slurry are mixed, are a good way to
67 determine if the addition of a particular amendment is appropriate to reduce P in surface
68 runoff from land applied slurry, but do not account for the interaction between applied slurry
69 and soil, and the effect of infiltration and skin formation on the release of P to surface runoff.
70 An agitator test, wherein an intact soil core, placed in a beaker, is overlain with continuously-
71 stirred water [8, 9], enables achievement of batch experiment results, but also simulates the
72 situation in which slurry is applied to soil, allowed to dry, and then subjected to overland
73 flow.

74

75 The aim of this study was to: (i) investigate the effectiveness of various pig slurry
76 amendments to control incidental P losses in runoff applied to permanent grassland; (ii)
77 identify optimum amendment application rates for each amendment; (iii) estimate the cost of
78 each treatment; and (iv) discuss the feasibility of using amendments in a real on-farm
79 scenario.

80

81 **2 Materials and Methods**

82

83 **2.1 Slurry collection and characterisation**

84

85 Pig slurry was taken from an integrated pig unit in Teagasc Research Centre, Moorepark,
86 Fermoy, Co. Cork. The sampling point was a valve on an outflow pipe between two holding
87 tanks, which were sequentially placed after a holding tank under the slats. To ensure a
88 representative sample, this valve was turned on and left to run for a few minutes before
89 taking a sample. The entire sample used for both the batch study and agitator test was taken
90 as one sample. The slurry was stored in a 25 L drum in a cold room at 11°C prior to testing.
91 The total phosphorus (TP) and total nitrogen (TN) were determined using persulfate
92 digestion. Ammonium-N ($\text{NH}_4\text{-N}$) was determined by adding 50 mL of slurry to 1 L of 0.1M
93 HCl, shaking, filtering through No. 2 Whatman filter paper, and analysing using a nutrient
94 analyser (Konelab 20, Thermo Clinical Lab systems, Finland). Slurry pH was determined
95 using a pH probe (WTW, Germany). Dry matter (DM) content was determined by drying at
96 105°C for 24 hr. The physical and chemical characteristics of the pig slurry used in this
97 experiment and characteristic values of pig slurry from other farms in Ireland and
98 internationally are presented in Table 1.

99

100 **2.2 Soil preparation and analysis**

101

102 Grassed soil samples were collected from a local dry stock farm in Galway, Republic of
103 Ireland. 120-mm-high, 100-mm-diameter aluminium (Al) coring rings were used to collect
104 undisturbed soil core samples (n=60). Soil samples (n=3) – taken from upper 100 mm from
105 the same location - were air dried at 40 °C for 72 hr, crushed to pass a 2 mm sieve and
106 analysed for soil test P using Morgan's extracting solution [10]. Soil pH (n=3) was
107 determined using a pH probe and a 2:1 ratio of deionised water-to-soil. The particle size
108 distribution was determined using a sieving and pipette method [11], and the organic content
109 of the soil was determined using the loss of ignition test [12]. The soil used was a poorly-
110 drained, sandy loam textured, topsoil (58% sand, 27% silt, 15% clay) with a soil test P of
111 $16.72 \pm 3.58 \text{ mg L}^{-1}$, total potassium of $127.39 \pm 14.94 \text{ mg L}^{-1}$, a pH of 7.65 ± 0.06 , and an
112 organic matter content of $13 \pm 0.1\%$.

113

114 **2.3 Batch study to determine potential amendments**

115

116 A batch study was carried out to identify appropriate amendments for the agitator test and the
117 rates at which they should be applied to pig manure to reduce water extractable P, an
118 environmental indicator of potential P loss in slurry. The following amendments were added
119 in the batch study: (i) commercial grade liquid alum (8% Al_2O_3) (ii) commercial-grade liquid
120 poly-Al chloride (PAC) (10 % Al_2O_3) (iii) commercial-grade liquid ferric chloride (38%
121 FeCl_3) (iv) analytical-grade ferric sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) (v) analytical-grade lime
122 ($\text{Ca}(\text{OH})_2$) (vi) flyash (vii) flue gas desulphurisation by-product (FGD) (viii) bottom ash (ix)
123 gypsum (x) aluminium-based water treatment residuals (Al-WTR), sieved to less than 2 mm
124 (Al-WTR-1), and (xi) Al-WTR homogenised sludge (Al-WTR-2). Tests i – v were applied

125 based on a metal:TP stoichiometric ratio and $v_i - x_i$ were applied based on a kg kg^{-1} weight
126 basis (slurry dry matter). The AI-WTR was provided by Galway City Water Treatment Plant.
127 Coal combustion by-products (flyash, FGD and bottom ash) were provided by the Electricity
128 Supply Board. The compositions of all the amendments used are shown in Table 2.

129

130 The pH of the amended slurry was measured after application of amendments at $t = 0$ h.
131 Amendments were added at 5 different rates to 50g of slurry and mixed for 10 s. All tests
132 were carried out in triplicate ($n=3$). At $t = 24$ h, samples were tested for water extractable P
133 after Kleinman et al. [13]. An unamended sample was also used as a study control.

134

135 **2.4 Agitator Test**

136

137 The agitator test has been used to investigate the release of P from soil [8] and from amended
138 dairy cattle slurry to soil [9]. This experiment replicates the way in which slurry is applied to
139 soil, allowed to dry, and then subjected to overland flow. Although no validation of test
140 results with actual runoff was undertaken, the test provided comparable conditions for
141 assessment of the effectiveness of the amendments at reducing the release of P from land-
142 applied slurry in a realistic way.

143

144 In the agitator test, the following treatments were examined in triplicate ($n=3$) within 21 d of
145 sample collection: a) a grassed sod-only treatment with no slurry applied; b) a grassed sod
146 with unamended slurry applied at a rate of 19 kg TP ha^{-1} (the control study); c) grassed sods
147 receiving amended slurry applied at a rate of 19 kg TP ha^{-1} . Six different amendments
148 (selected from the batch study above) were applied at three different rates (low, medium and
149 high) based on the results obtained from the batch study. Amendments were added to slurry

150 in a 100 mL plastic cup and mixed for 10 s. Prior to the start of the agitator test, the intact soil
151 samples – at approximately field capacity – were taken from their sampling cores and cut to a
152 height of 45 mm; this was considered sufficient to include the full depth of influence on
153 release of P to overland flow [8]. They were then transferred into 1 L glass beakers. The
154 slurry and amended slurry was then applied to the soil cores ($t = 0$ h) and left to interact for
155 24 h prior to the sample being saturated. At $t = 24$ h, the samples were gently saturated by
156 adding deionised water to the soil at intermittent time intervals over 24 h until water pooled
157 on the surface. Immediately after saturation ($t = 48$ h), 500 mL of deionised water was added
158 to the beaker. The agitator paddle was lowered to mid-depth in the water overlying the soil
159 sample and the paddle was set to rotate at 20 rpm for 30 h to simulate overland flow (Figure
160 1).

161
162 Water samples (4 ml) were taken from mid-depth of the water overlying the soil at 0.25, 0.5,
163 1, 2, 4, 8, 12, 24 and 30 h after the start of each test (i.e after the 500 ml was added). All
164 samples were filtered immediately after sample collection using 0.45 μm filters and prior to
165 being analysed colorimetrically for DRP using a nutrient analyser (Konelab 20, Thermo
166 Clinical Labsystems, Finland). pH readings were taken in the overlying water at 1 h and 30 h
167 after the start of each test.

168

169 **2.5 Cost**

170

171 The effects of amendments on slurry viscosity or handling were not considered in the cost
172 analysis. It was assumed that amendments would be added upon delivery, so storage cost on
173 site was excluded from the analyses. In the case of lime, the cost was estimated using

174 commercial grade lime. The calculated costs took into account the fixed and operational costs
175 for a 75 kW tractor and 2000 gal. splash-plate slurry tanker.

176

177 **3 Results**

178

179 **3.1 Batch study**

180

181 The most effective amendments at reducing water extractable P after 24 h were (in decreasing
182 order of effectiveness): alum (99%), lime (99%), ferric chloride (98%), PAC (95%), flyash
183 (87%), FGD (76%), gypsum (39%), ferric sulphate (27%), bottom ash (24%), Al-WTR-2
184 (15%) and Al-WTR-1 (0%) (Figure 2).

185

186 For all solutions, there was a point beyond which further additions of amendments did not
187 significantly reduce water extractable P (Figure 2). On the basis of inspection of the results,
188 the amendments and their application rates to be used in the agitator test were: (i) alum
189 (0.29:1, 0.58:1, 0.88:1 [Al:P]); (ii) PAC (0.18:1, 0.36:1, 0.72:1 [Al:P]); (iii) ferric chloride
190 (0.34:1, 0.62:1, 0.89:1 [Fe:P]); (iv) lime (3.86:1, 5.79:1, 7.79:1 [Ca:P]); (v) flyash (0.857,
191 1.71, 3.43 kg kg⁻¹ DM); and (vi) FGD (2.7, 3.78, 4.86 kg kg⁻¹ DM).

192

193 **3.2 Agitator test**

194

195 Figure 3 shows the mass of DRP in the overlying water and DRP concentrations over the
196 study duration. The percentage reduction in DRP for each treatment at each rate is shown in
197 Table 3. The unamended slurry had a DRP concentration of 17.8 mg L⁻¹ in the overlying
198 water. The DRP concentrations in the overlying water, ranked from best to worst, were: alum,

199 2.5 mg L⁻¹; FGD, 4.6 mg L⁻¹; PAC, 4.7 mg L⁻¹; ferric chloride, 5.2 mg L⁻¹; flyash, 7.5 mg L⁻¹;
200 and lime, 8.1 mg L⁻¹. These compare to the water overlying the grassed sod-only treatment,
201 which had a DRP concentration of 2.0 mg L⁻¹.

202

203 **3.3 Cost**

204

205 Table 3 shows the estimated cost of addition of amendments and estimations of spreading and
206 agitation costs as a result of their use. In order of increasing cost of use, per m³ of pig slurry,
207 they are: ferric chloride (€1.89); flyash (€2.00); PAC (€2.09); alum (€2.18); lime (€2.84) and
208 FGD (€4.10). Figure 4 shows the total cost of amendment (€ tonne⁻¹) versus percentage
209 reduction in DRP release to overlying water (%) and the reduction in DRP released from soil
210 (kg ha⁻¹). The addition of FGD led to dry matter contents of above 10%, which would require
211 water to be added to produce dry matter of a low enough consistency for slurry spreading
212 operations. Addition of water would require agitation and these, combined with the high
213 volume of addition per m³, significantly increased the total cost of FGD above the other
214 amendments. Alum, although clearly the best performing amendment, was still competitively
215 priced compared to the other amendments.

216

217 **4 Discussion**

218

219 In the batch study, Al-WTR- 1 and Al-WTR-2 increased the water extractable P of the slurry
220 when added at some weights. This may be attributable to the fact that there were small
221 quantities of P within Al-WTR- 1 and Al-WTR-2 (Table 2). There was also P present in
222 flyash and FGD, but these amendments contained much more calcium (Ca) and magnesium
223 (Mg), which are P sorbing elements. Lime required a much higher stoichiometric addition

224 rate to achieve significant water extractable P reduction, however this is acceptable as lime is
225 often added to land by farmers and has widespread public acceptance. Ferric sulphate was not
226 tested above a stoichiometric rate of 0.332, as there was a poor response relative to the other
227 amendments at the same addition rate. The reduction in water extractable P compared
228 favorably to that of Dao et al. [7], who reported reductions of 60% and 85% in water
229 extractable P concentrations after adding alum and flyash, respectively, to stockpiled cattle
230 manure.

231

232 Taking into account costs, land application of metals and potential DRP reductions in
233 overlying water, the amendments, ranked in decreasing order of feasibility, were: alum, ferric
234 chloride, PAC, flyash, lime and FGD.

235

236 There was a high initial rise in DRP at the start of each test, with the rate of increase reducing
237 over time towards the end of the study (Figure 3). It can be seen in almost all cases that the
238 higher the addition rate for each amendment, the lower the peak in DRP concentration. The
239 amendments used in the agitator test all reduced the DRP concentrations in the overlying
240 water. However, they did not reduce the concentrations to below that of the grassed sod-only
241 treatment, which itself was well above $30 \mu\text{g P L}^{-1}$, the median phosphate level above which
242 significant deterioration may be seen in river ecosystems [14]. The reason for this is the
243 amendments only reduce the contribution of the slurry to the overlying water DRP and do not
244 affect the contribution of the soil to the overlying water DRP. The reductions in DRP were
245 broadly similar to Smith et al. [5], who achieved reductions in DRP of 84% in runoff water
246 when adding both alum and AlCl_3 to pig slurry at 430 mg Al L^{-1} in a field-based study.

247

248 The effect of amendments on slurry pH is a potential barrier to their implementation as it
249 affects P sorbing ability [15] and ammonia (NH₃) emissions from slurry [16]. The use of
250 acidifying amendments can lead to increased release of hydrogen sulphide gas (H₂S) from
251 slurry, which is believed to be responsible for human and animal deaths when slurry is being
252 agitated on farms. However, the results from this experiment show the pH of the overlying
253 water not to be significantly affected by the use of amendment.

254

255 From the cost analysis, it can be seen that the use of amendments may only be worth pursuing
256 where focused application may be adopted. As legislation allows less slurry to be spread on
257 high P index soils, farmers with these soils have less land available on which to spread slurry.
258 The addition of amendment to pig slurry has the potential to relieve this problem. If a farmer
259 has more than one P index level on a farm, then a way to potentially reduce the cost
260 associated with amending the slurry would be to only amend the slurry that is applied to areas
261 of the farm with a higher soil test P. However, this will only reduce the impact of
262 landspreading on the potential loss of P in runoff and will not impact on the soil test P, which
263 will still be a potential pollution source.

264

265 Although this study did not investigate the release of metals due to the amendment of slurry,
266 previous studies that have found no added risk was posed by amending land applied pig [4] or
267 poultry [17] manure. Moore et al. [17] also investigated whether using alum as an amendment
268 affected Al concentrations in the soil or Al uptake by plants. They showed that the use of
269 alum did not negatively affect either. The reason that Al availability was not affected is
270 because Al availability in soils is virtually independent of the level of total Al, but instead is
271 controlled by the geochemical conditions present, with pH being the major influencing factor.
272 Acidic conditions result in the dissolution of clay minerals and Al oxides, causing high

273 concentrations of exchangeable Al. The pH would be expected to increase, resulting in
274 decreased available Al. Moore et al. [17] also calculated that it would take up to 400 years of
275 annual application of alum-treated litter to increase the level of total Al in the soil from 7 to
276 8%, as alum is already the most abundant metal in most soils.

277

278 **5 Conclusions**

279

280 The findings of this study are:

- 281 1. All of the amendments trialled in the agitator test have the potential to reduce the
282 release of P in surface runoff from land-applied slurry.
- 283 2. Taking into account costs and land application of metals, suitable amendments which
284 may reduce the risk of surface runoff of P from land applied pig slurry are (in
285 decreasing order of feasibility): alum, ferric chloride, PAC, flyash, lime and FGD.
- 286 3. As there are significant costs associated with the use of these amendments, it is
287 recommended that they are used strategically in areas which are likely to have
288 potential nutrient loss problems. As land surrounding pig farms tend to have high soil
289 test phosphorus, the use of amendments may be deemed necessary. Although they
290 reduce the impact of nutrient loss from land application of pig slurry, they do not
291 prevent the loss of nutrients from soil of high nutrient content.

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299

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420 **Legend**

421

422 **Figure 1.** The agitator experimental setup.

423 **Figure 2.** Concentration of water extractable P in pig slurry (mg L^{-1}) as a function of
424 stoichiometric ratio of Al added as alum and poly-Al chloride (PAC); Fe added as ferric
425 chloride and ferric sulphate; and Ca as lime to total P in pig slurry (a), and mass of flyash,
426 flue gas desulphurization by-product (FGD), bottom ash, gypsum, and Al-based water
427 treatment residuals sieved to less than 2 mm (Al-WTR- 1) and homogenized sludge (Al-
428 WTR-2) added per dry matter of pig slurry (b).

429 **Figure 3.** The mass of dissolved reactive P (DRP) (mg m^{-2}) and DRP concentration (mg L^{-1})
430 in water overlying grassed sod-only treatment; grassed sod with unamended slurry; and
431 grassed sod with slurry amended with alum, poly-Al chloride (PAC), ferric chloride, lime,
432 flyash and flue gas desulphurization by-product (FGD), each applied at three different rates,
433 plotted over the 30 h of the test.

434 **Figure 4.** Total cost of amendment (€ tonne^{-1}) of pig slurry plotted against the reduction in
435 dissolved reactive P (DRP) lost to overlying water (kg ha^{-1}) and the percentage reduction in
436 DRP release to overlying water from slurry amended with alum, poly-Al chloride (PAC),
437 ferric chloride, lime, flyash and flue gas desulphurization by-product (FGD), each applied at
438 three different rates.

439 Table 1. Physical and chemical characteristics of the pig slurry used in this experiment and
 440 characteristic values of pig slurry from other farms in Ireland and internationally.

Location	Total P (mg L ⁻¹)	Total N (mg L ⁻¹)	Total K (mg L ⁻¹)	NH ₄ -N (mg L ⁻¹)	pH	Dry matter (%)	Reference
Ireland	560	2150±212		1248 ±40	8.9 ± 0.3	3.5± 0.2	The present study
	800	4200					S.I. No. 610 of 2010
	1630	6621	2666			5.77	18 ^a
	900±7	4600±21	2600±10			3.2±2.3	19 ^a
Spain	820	3220	1008	1860	7.59	3.2	20
U.S.A.	707	2037	1412	1366		2	21

441 a) Values changed to mg L⁻¹ assuming densities of 1 kg L⁻¹.

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456 Table 2. Characterisation of amendments used in the batch and agitator tests (mean \pm standard deviation) tests carried out in triplicate.

Amendment	Alum	Poly-Al chloride	Ferric Chloride	Ferric Sulphate	Lime	Flyash	FGD	Bottomash	Gypsum	Al-WTR-1	Al-WTR-2
	8% Al ₂ O ₃	10 % Al ₂ O ₃	38% FeCl ₃	FeSO ₄ .7H ₂ O	Ca(OH) ₂					(<2mm)	(sludge)
pH	1.25	1.0 – 3.0				11.2 \pm 0.04	8.6 \pm 0.0			7.9 \pm 0.1	6.9 \pm 0.2
WE ^a	mg kg ⁻¹	0				<0.01	<0.01			<0.01	
Al	4.23					5.7 \pm 0.2	0.1 \pm 0.0	0.42	1.1	11 \pm 0.0	5.3 \pm 0.2
Ca					54.1	4.9 \pm 0.2	20 \pm 0.3	0.4	28	1.3 \pm 0.1	0.11
Fe	%	<0.01	38	20		2.2 \pm 0.1	0.1 \pm 0.0	1.6	0.5	0.2 \pm 0.0	0.01
K						0.1	0.03	0.04	0.01	0.03 \pm 0.0	<0.01
As	1	<1.0	<2.8			13 \pm 0.6	<0.01			6.2 \pm 1.1	<0.01
Cd	0.21	<0.2	<3.4			0.6 \pm 0.0	0.2 \pm 0.02	0.28		0.16 \pm 0.0	<0.01
Co						33 \pm 1	0.3 \pm 0.1	0.43		0.5 \pm 0.3	<0.01
Cr	2.1	<2.0	<48			88 \pm 2	3 \pm 0.1	14.3		3.8 \pm 0.21	0.3 \pm 0.02
Cu			<65			32.7 \pm 1.5	37 \pm 13	8.1		31.7 \pm 1.5	0.6 \pm 0.03
Mg						12,200 \pm 610	2,950 \pm 58	2120	12,061	165 \pm 33	3.2 \pm 1.7
Mn			<1370			347 \pm 160	31 \pm 0.6	92		79 \pm 1	6.9 \pm 0.1
Mo						7.7 \pm 0.5	0.73 \pm 0.3	0.63		0.47 \pm 0.2	<0.01
Na						1370 \pm 610	660 \pm 93	859	371	611 \pm 180	65 \pm 14
Ni	mg kg ⁻¹	<1.0	<48			44 \pm 1	11 \pm 0.6	9.9		4.8 \pm 0.06	0.6 \pm 0.2
P						5460 \pm 630	65 \pm 20	171	218	234 \pm 5.3	18.7 \pm 1.6
Pb	2.8	<2.0	<14			30 \pm 2	0.74 \pm 0.4	3.9		1.2 \pm 0.8	<0.01
V						155 \pm 5	49 \pm 2	13.7		3 \pm 0.2	0.2 \pm 0.01
Zn						75 \pm 31	9.4 \pm 2	19.7		17	0.8 \pm 0.1
Sb		<1.0	<2.8								
Se		<1.0	<2.8								
H ₂ O		<0.2	<0.7								

WE^a-water extractable phosphorus; Al-WTR-alum-based water treatment residual; FGD-flue gas desulphurisation product.

457 Table 3. Table showing amendments in order of feasibility score, breakdown of costs^a, cost/m³ slurry^b, cost for 500 sow integrated unit,
458 percentage reduction in DRP in overlying water at 30 h.

Amendment ^c	Feasibility score	Addition rate ^d	Cost ^e	Rate	Cost of amendment	Spreading	Agitation	Cost water ^f	Total	500 sow integrated unit ^g	DRP Removal	Spreading rate of metal	Within max allowable metal spreading rates ^h
			€/tonne	kg/m ³	€/m ³	€/m ³	€/m ³	€/m ³	€/m ³	€/farm	%	kg/ha	Yes/No
Control					0.00	1.56	0.00	0.00	1.56	16,182	0		
Alum	1	0.29:1 Al: P	150	4	0.58	1.60	0.00	0.00	2.18	22,672	55	5.51	No limit
		0.58:1 Al: P		8	1.16	1.56	0.00	0.00	2.72	28,309	64	11.02	
		0.88:1 Al: P		12	1.76	1.57	0.00	0.00	3.33	34,613	86	16.72	
Ferric Chloride	2	0.34:1 Fe: P	250	1	0.34	1.55	0.00	0.00	1.89	19,704	48	6.46	No limit
		0.62:1 Fe: P		2	0.62	1.55	0.00	0.00	2.18	22,655	52	11.78	
		0.89:1 Fe: P		4	0.90	1.56	0.00	0.00	2.45	25,500	71	16.91	
Poly-Al chloride	3	0.18:1 Al: P	280	2	0.53	1.55	0.00	0.00	2.09	21,689	43	3.42	No limit
		0.36:1 Al: P		4	1.07	1.56	0.00	0.00	2.62	27,258	42	6.84	
		0.72:1 Al: P		8	2.13	1.56	0.00	0.00	3.69	38,396	73	13.68	
Flyash	4	0.030 kg/kg	14	30	0.40	1.6	0.00	0.00	2.00	20,815	43		Yes
		0.060 kg/kg		60	0.81	1.64	0.00	0.00	2.45	25,488	48		
		0.120 kg/kg		120	1.62	1.74	0.00	0.00	3.36	34,910	58		
Ca(OH) ₂ (Lime)	5	3.86:1 Ca: P	312	4	1.28	1.56	0.00	0.00	2.84	29,511	30	73.34	No limit
		5.79:1 Ca: P		6	1.92	1.56	0.00	0.00	3.48	36,206	53	110.01	
		7.71:1 Ca: P		8	2.56	1.56	0.00	0.00	4.12	42,866	54	146.49	
FGD	6	0.095 kg/kg	14	95	1.28	1.98	0.43	0.42	4.10	42,634	66		Yes
		0.132 kg/kg		132	1.79	2.49	0.54	1.09	5.91	61,467	67		
		0.170 kg/kg		170	2.3	2.98	0.64	1.73	7.64	79,474	74		

DRP-dissolved reactive P; FGD-flue gas desulphurisation product; a) Calculations based on an integrated pig unit with 500 sows, or equivalent stocking rate, indoors for 52 weeks; b) Slurry properties: Total P = 560 mg L⁻¹ and 3.5% dry matter (DM); c) In the case of Ca(OH)₂, cost was estimated using commercial grade lime; d) Addition rates for Flyash and FGD quoted as kg of ammendment/kg of slurry; e) Cost includes delivery of material and addition of material to slurry in storage tank; f) Addition of some amendments resulted in DM >10%-water addition needed for spreading. In this case, agitation is required for process of adding water; g) Calculations based on 0.4 m³ of slurry/sow/week; h) Max allowable metal application rates take from S.I. No. 267/2001 -Waste Management (Use of Sewage sludge in Agriculture) (Amendment) Regulations, 2001 (www.irishstatutebook.ie).

Figure 1.



Figure 2 b).

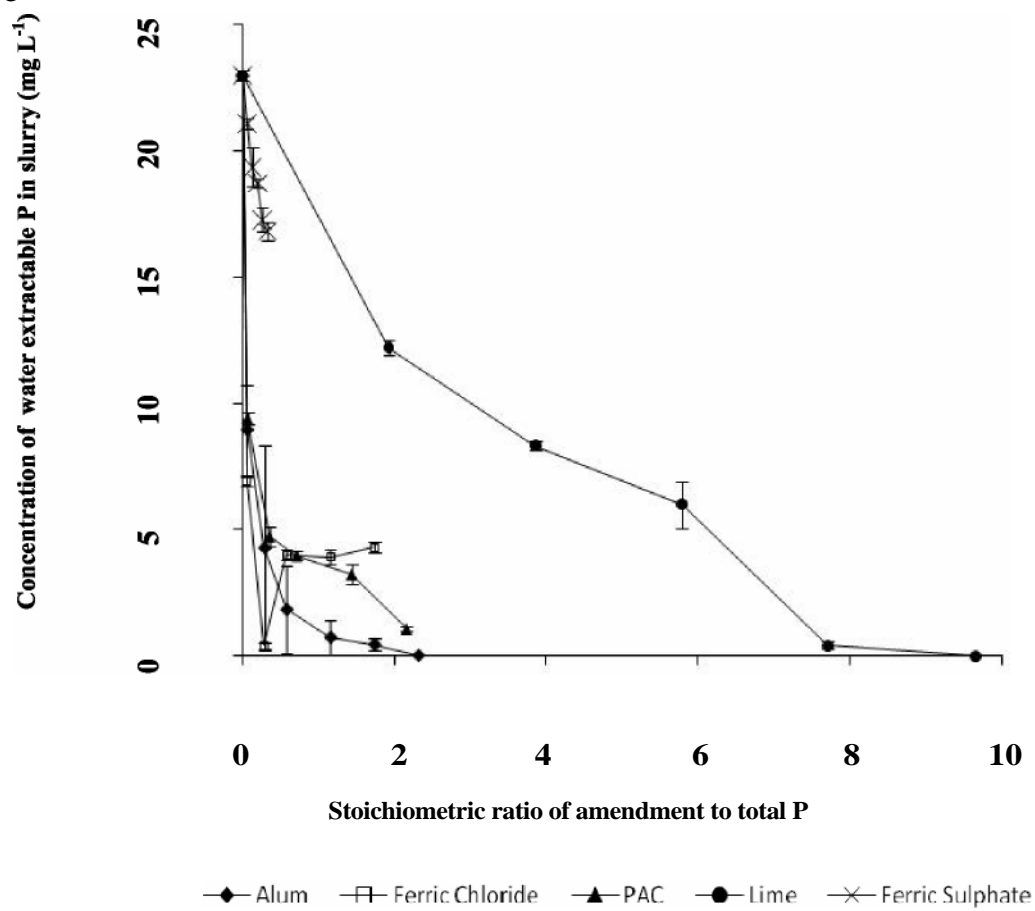


Figure 2 b).

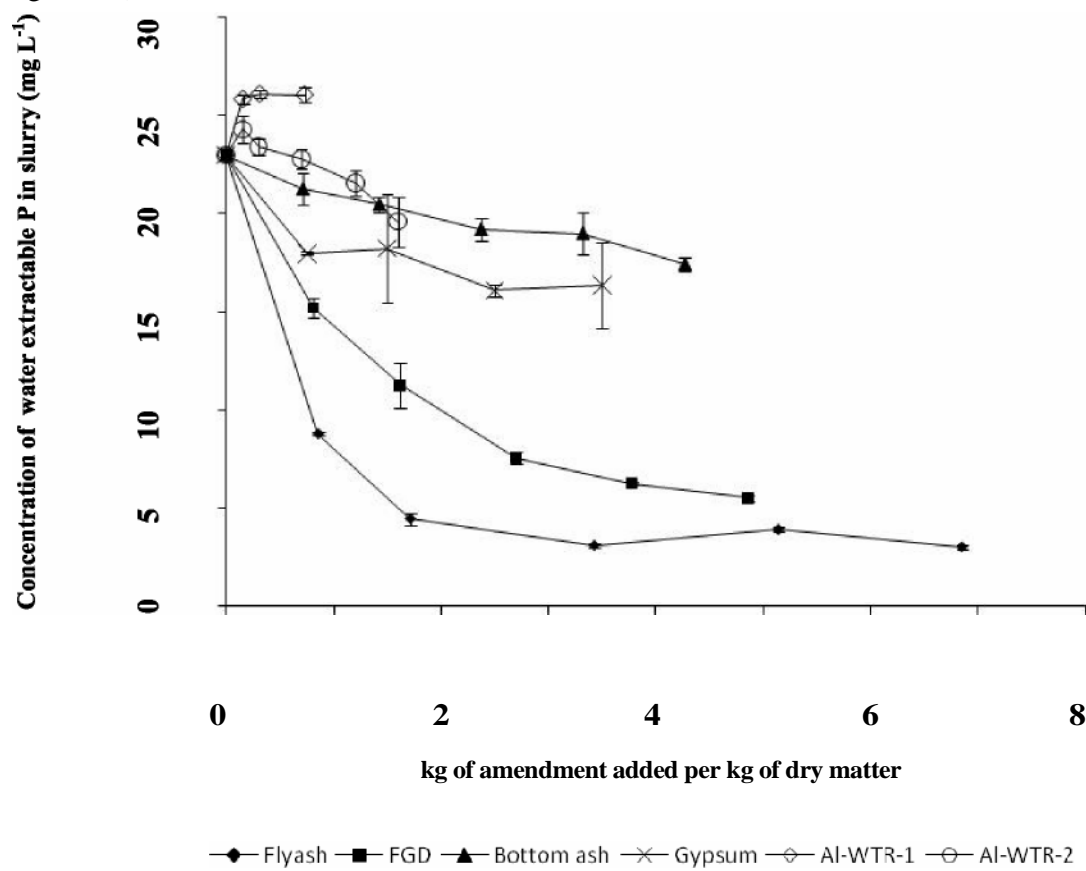


Figure 3.

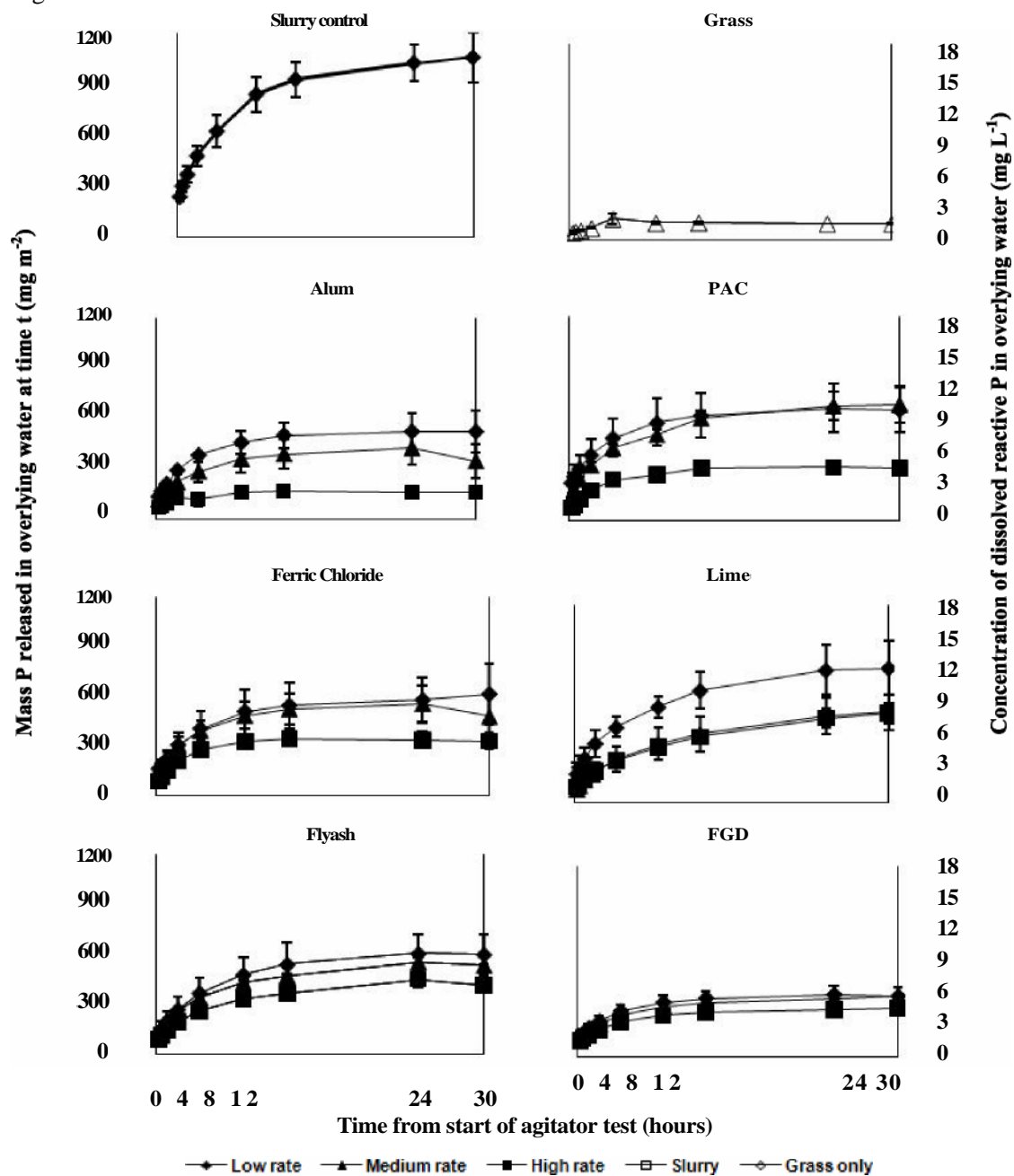


Figure 4.

